The Unique Signature of Shell Curvature in Gamma-Ray Bursts

Alicia Margarita Soderberg[1] and Edward E. Fenimore[2]

[1] DAMTP, Silver Street, Cambridge CB3 9EW, ENGLAND
[2] Los Alamos National Laboratory, Los Alamos NM 87545, USA

Abstract. As a result of spherical kinematics, temporal evolution of received gamma-ray emission should demonstrate signatures of curvature from the emitting shell. Specifically, the shape of the pulse decay must bear a strict dependence on the degree of curvature of the gamma-ray emitting surface. We compare the spectral evolution of the decay of individual GRB pulses to the evolution as expected from curvature. In particular, we examine the relationship between photon flux intensity (I) and the peak of the $\nu F\nu$ distribution (E_{peak}) as predicted by colliding shells. Kinematics necessitate that E_{peak} demonstrate a power-law relationship with I described roughly as: $I = E_{peak}^{(1-\zeta)}$ where ζ represents a weighted average of the low and high energy spectral indices. Data analyses of 24 observed gamma-ray burst pulses provide evidence that there exists a robust relationship between E_{peak} and I in the decay phase. Simulation results, however, show that a sizable fraction of observed pulses evolve faster than kinematics allow. Regardless of kinematic parameters, we found that the existence of curvature demands that the $I - E_{peak}$ function decay be defined by $\sim (1-\zeta)$. Efforts were employed to break this curvature dependency within simulations through a number of scenarios such as anisotropic emission (jets) with angular dependencies, thickness values for the colliding shells, and various cooling mechanisms. Of these, the only method successful in dominating curvature effects was a slow cooling model. As a result, GRB models must confront the fact that observed pulses do not evolve in the manner which curvature demands.

1 Introduction to the Kinematic Model

The simulated pulses described in this study were created through code based strictly on kinematics. Simulated shells were collided with one another, thereby conserving energy and momentum and the resulting energy was distributed into standard Band function spectra. Isotropic emission from the merged shell was (initially) assumed where the entirety of the shell is modeled to be gamma-ray active. Figure 1 demonstrates the geometry of the model. Time of arrival is determined by the angle, θ, at which the emitting patch lies with respect to the line of sight. Off axis emission is received later than on axis emission by a factor of $R(1-cos\theta)$. The emitting shell has a slight thickness defined between $R/c = t_{max}$ and $R/c = t_0$. Photons within shell volume dV contribute to the pulse shape between received times, T and $T + dT$. As a result of the relativistic motion of the shell, the volume of emitting material which contributes to the received signal at any time is constant. Emitting patches on the shell which fall between the two ellipsoids labeled T and $T + dT$ will arrive at the detector within this range of received time.

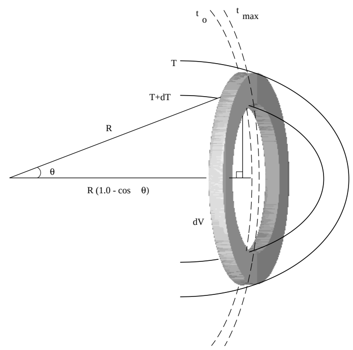

Fig. 1. Geometry of the Kinematic Model

2 Discussion: The Robust Curvature Dependency

Results of the kinematic studies demonstrate that the $I - E_{peak}$ relationship is a robust indicator of shell curvature. The strength of this relation was analyzed by varying both Band and kinematic parameters for the shell model. Observed pulses, however, do not demonstrate this dependence (see Figures 2 and 3). In the attempt to break spherical symmetry and reduce the dependence of pulse shape on curvature effects, more complicated emission models were simulated. These models enabled further testing to examine the possibility of additional dependencies which were not included in the original kinematic code. Models explored jetting the model emission into an opening angle between 0.1-5.0 degrees and allowing for intrinsic angular dependencies of the Lorentz factor and/or E_{peak} across the skullcap. Off-axis shell collisions were simulated such that the collision time was not instantaneous in the rest frame of the central engine and the initial photon emission occurred at an angle outside the critical beaming angle. Various thicknesses were applied to the emitting shell but this only proved to distort the rise time of the pulse and did not have any effect on the shape of the pulse decay or the $I - E_{peak}$ relationship. Models also explored fast and slow

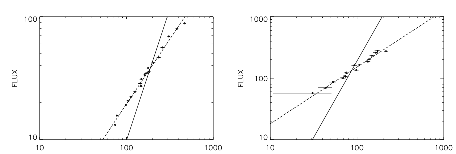

Fig. 2. Comparison with BATSE pulses. Simulations were compared with a data set of 24 pulses selected from the BATSE GRB Spectral Catalog I (Preece et al.,1999). The top figure displays the robustness of the expected and observed $I - E_{peak}$ relationships for GRB921207. The solid line represents the expected decay index as predicted by colliding shells. It is evident that there is a large discrepancy between the data and the simulations. The same is true for the bottom figure which displays the results for GRB970201.Through these cases, the severity of this discrepancy can be clearly seen.

cooling mechanisms. Generally, it was found that the curvature dependence is fairly difficult to break, and requires either grossly distorted geometries and/or relatively long cooling time scales. It was found that the emitting shell must

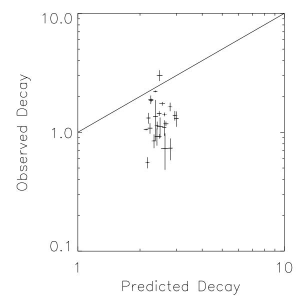

Fig. 3. **Comparison of Expected $I - E_{peak}$ Decay with Observed $I - E_{peak}$ Decay from BATSE Pulses.** The solid line represents the $I - E_{peak}$ decay index demanded by colliding shells. Curvature and special relativity impose such a relationship because later portions of the pulse arrive from off-axis emission. This results in an expected decay index of $I = E_{peak}^{(1-\zeta)}$. The majority of BATSE observations lie below the solid line therefore indicating that observed $I - E_{peak}$ decay is slower than the decay predicted by kinematics.

cool for a time period of approximately $t_{cool} = R/c$ in the detector rest frame (where $R/c < \Gamma^2$). This corresponds to a comoving time of $t'_{cool} = R/c\Gamma$ and an arrival time of $T_{cool} = R/c\Gamma^2$ by the standard transformations. As a result, the observed cooling time was comparable in length to the duration due to curvature (e.g. 10^4 s). Such slow cooling overwhelmed the curvature dependency with cooling effects throughout the entire length of the pulse, thereby allowing for a new pulse shape evolution. It is emphasized that slow cooling was the only method included in this study which was able to break the robust curvature dependency as imposed by the kinematics of two colliding shells. Typical cooling times, however, are commonly quoted as being shorter than the duration of the pulse (e.g. $< 10^4$ s). A remedy to this situation is to minimize the timescale on which curvature effects can be detected by reducing the radius and/or increasing the bulk Lorentz factor of the emitting shell. This, in turn, allows for a relatively shorter cooling time. Long cooling times, however, face a number of problems including efficiency considerations which must be addressed.

References

1. Band, D. et al.: ApJ **413**, 281 (1993)
2. Crider, A., et al.: ApJ **519**, 206 (1999)
3. Fenimore, E. E., Madras, C. D., & Nayakshin, S.: ApJ **473**, 998 (1996)
4. Preece, R. D., et al.: ApJ Supp. **126**, 19 (1999)
5. Rybicki, G. B. & Lightman, A. P.: *Radiative Processes in Astrophysics*, 1979
6. Sari, R., & Piran, T.: ApJ **485**, 270 (1997)
7. Summer, M. C., & Fenimore, E. E.: AIP Proc. **428**, 765 (1998)